# National Aeronautics and Space Administration

# ROSAT

## Annual Status Report
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**"EGRET Sources at Intermediate Galactic Latitude"**

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# SUMMARY

During the period 1 November 1995 through 31 October 1996, five papers using *ROSAT* data, supported in part by this grant, were published in refereed journals. Their bibliographical references are listed in the Appendix, and they will not be discussed further in this report. (Preprint versions of these were included in last year's report). In addition, four papers using *ROSAT* data, were submitted to refereed journals during the current reporting period. The abstracts of these papers are given in the next four sections of this report, and their status is given in the Appendix. Finally, two new projects for which *ROSAT* data were recently received are currently being studied under this grant. A summary of work in progress on these new projects is given in the last two sections of this report.

# 1. Extreme X-ray Variability In The Narrow-Line QSO PHL 1092

Karl Forster and Jules P. Halpern

A *ROSAT* observation of the narrow-line Fe II QSO PHL 1092 shows rapid variability that requires an efficiency of at least 0.13, exceeding the theoretical maximium for an accretion disk around a non-rotating black hole. Plausible explanations for its high efficiency incorporate anisotropic emission and/or accretion onto a rapidly rotating black hole, the latter recently suggested by Kwan et al. as a mechanism for generating PHL 1092's strong Fe II lines by mechanical heating in an accretion disk. The soft X-ray luminosity of PHL 1092 had also increased by a factor of 21 over the weak *Einstein* detection, to more than $5 \times 10^{46}$ ergs s$^{-1}$. Its photon spectral index of 4.2 is among the steepest of any AGN. These X-ray properties are characteristic of narrow-line Seyfert 1 galaxies, of which PHL 1092 is evidently a very luminous member. Narrow-line QSOs also extend a significant correlation between X-ray luminosity and X-ray spectral index which we have found among a large sample of optically-selected, narrow-line Seyfert 1 galaxies observed by *ROSAT*.

# 2. THE GEMINGA PULSAR:
# SOFT X-RAY VARIABILITY AND AN *EUVE* OBSERVATION

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We observed the Geminga pulsar with the *EUVE* satellite, detecting pulsed emission in the Deep Survey imager. Joint spectral fits of the *EUVE* flux with *ROSAT* PSPC data are consistent with thermal plus power-law models in which the thermal component makes the dominant contribution to the soft X-ray flux seen by *EUVE* and *ROSAT*. The data are consistent with blackbody emission of $T = (4 - 6) \times 10^5$ K over most of the surface of the star at the measured parallax distance of 160 pc. Although model atmospheres are more realistic, and can fit the data with effective temperatures a factor of 2 lower, current data would not discriminate between these and blackbody models. We also find evidence for variability of Geminga's soft X-ray pulse shape. Narrow dips in the light curve that were present in 1991 had largely disappeared in 1993/1994, causing the pulsed fraction to decline from 32% to 18%. If the dips are attributed to cyclotron resonance scattering by an $e^{\pm}$ plasma on closed magnetic field lines, then the process that resupplies that plasma must be variable.

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# 3. A BROAD-BAND X-RAY STUDY OF THE GEMINGA PULSAR

J. P. HALPERN & F. Y.-H. WANG

We present a comprehensive study of the Geminga pulsar at energies 0.1–10 keV using data from the *ASCA*, *ROSAT*, and *EUVE* satellites. The bulk of the soft X-ray flux can be parameterized as a blackbody of $\dot{T} = (5.6 \pm 0.6) \times 10^5$ K, occupying a fraction 0.10–0.64 of the surface area of the neutron star at the parallax distance of 160 pc. The *ASCA* detection of Geminga resolves the nature of the harder X-ray component previously discovered by *ROSAT* in favor of nonthermal emission, rather than thermal emission from a heated polar cap. The hard X-ray spectrum can be fitted by a power-law of energy index $1.0 \pm 0.5$. The hard X-ray light curve has a strong main peak and a weak secondary peak; its total pulsed fraction is $\approx 55\%$. Three *ROSAT* PSPC observations show significant variability of Geminga's light curve. In particular, a peculiar energy dependence of the modulation in the soft X-ray component, dubbed the "Geminga effect" in the original PSPC data, is not present in later observations. In addition, fine structure in the soft X-ray light curve, interpreted as eclipses due to cyclotron resonance scattering by a plasma screen on the closed magnetic field lines, almost disappeared in the most recent observations. All of the variable properties of Geminga can probably be associated with the nonthermal process that supplies $e^{\pm}$ pairs to its

# 4. Classification of *IRAS*-Selected X-ray Galaxies
# in the *ROSAT* All-Sky Survey

E. C. Moran, J. P. Halpern, & D. J. Helfand

To explore the possibility that star-forming galaxies or obscured Seyfert galaxies, both of which are known to be luminous infrared sources, contribute significantly to the cosmic X-ray background, we have carried out an extensive program to obtain accurate spectroscopic classifications of the Boller et al. (1992) catalog of *IRAS* sources detected in the *ROSAT* All-Sky Survey. This has involved careful optical spectroscopy, a review of the literature, and efforts to reveal of the contaminants in the sample. Classifications have been determined for 210 of the 241 X-ray sources in the catalog; 105 are presented here for the first time. A large number of IR/X-ray source chance coincidences are found in this sample; of the 40–50 expected, we have firmly identified 18 and have established strong cases for 29 others. Most chance coincidences involve bright stars or Seyfert galaxies close (in projection) to IR-bright H II galaxies. Although this work was initially motivated by the report that a new class of X-ray–luminous, normal spiral galaxies was to be found in this sample, we find no evidence for such a class. Most of the extragalactic X-ray sources are active galactic nuclei (AGNs), consistent with the results of previous studies of X-ray–selected objects. However, many of these AGNs exhibit weak or heavily reddened Seyfert features in their optical spectra. In addition, two rare types of AGNs are found in this sample with surprising frequency: I Zw 1 objects (also called narrow-line Seyfert 1s) and starburst/Seyfert composite galaxies, a new class of luminous X-ray sources. We have shown that the Boller et al. object 202103–223434 (= *IRAS* 20181–2244), reported to be the best example of a narrow-line quasar, is actually a member of the I Zw 1 class. The enigmatic starburst/Seyfert composite galaxies have optical spectra dominated by the features of H II galaxies, yet X-ray luminosities typical for Seyfert galaxies. Close examination of their optical spectra reveals subtle Seyfert signatures: O [III] lines broader

than all other lines in the spectrum and, in some cases, a weak, broad H $\alpha$ component. Obscuration of the active nucleus is likely to explain the X-ray and optical properties of these objects. We describe a scenario in which such optically innocuous, obscured AGNs could comprise an important new component of the X-ray background.

## 5. De-Identifying a Non-AGN

This observation was meant to resolve an important loose end in our program of classification of X-ray luminous emission-line galaxies. The *Einstein* X-ray source E 0336–248 was classified as a Seyfert galaxy at $z = 0.043$ by Pravdo & Marshall (1984), and now appears in all the standard quasar catalogs, as well as in a list of bright quasars for absorption line studies with the *HST* (Bowen *et al.* 1994). But a high-quality spectrum that we recently obtained demonstrates that the galaxy has only narrow emission lines of ordinary H II regions, with no evidence for AGN activity. This might cause a flurry of speculation if anyone finds out, because the implied X-ray luminosity of $3 \times 10^{43}$ ergs s$^{-1}$ is vastly in excess of that observed from any quiescent or starburst galaxy. Instead, we suspected that this emission-line galaxy is actually a misidentification of the X-ray source. The goal of this observation was to decide the identification one way or another using a short (3000 s) HRI observation to obtain an accurate X-ray position.

Non-AGN emission-line galaxies are very common, so occasional misidentification of one with an X-ray source might be excused. The reader might justifiably ask, "Why bother with the X-ray de-identification of a non-AGN when there are so many real X-ray AGNs to be studied?" In fact, considerable observational resources are being expended by several groups that are searching for precisely this chimera, the X-ray luminous starburst galaxy. Although the vast majority of emission-line galaxies with soft X-ray luminosities in excess of $10^{42}$ ergs s$^{-1}$ are Seyferts, speculation recurs that some of these might be "normal" star forming galaxies (Fruscione & Griffiths 1991; Boller et al. 1992; Boller, Fink, & Schaeidt 1994; Boyle et al. 1995; Griffiths et al. 1995), in which the X-rays arise in the course of normal stellar evolution from numerous massive X-ray binaries. These proposals are motivated in part by the need to find a populous new class of high-luminosity X-ray emitters to constitute the X-ray background. Among these investigators, this particular galaxy could provoke needless theoretical speculation and the squandering of much telescope time. It has already caused a little bit of that for us. Instead, the

problem could be put to rest with less HRI observing time than has already been devoted to this object, either in X-rays or optically.

For us, establishing the X-ray properties of this emission-line galaxy is part of an extensive program to reevaluate nearly all such candidates from the *Einstein* IPC source list, as well as from the *ROSAT/IRAS* All-Sky Survey. We have already found a ubiquitous absence of evidence for "starburst" galaxies with $L_X > 10^{42}$ ergs s$^{-1}$ among the *ROSAT* sources, and in the *Einstein* Extended Medium Sensitivity Survey. Most of the ambiguous cases turn out to have previously unrecognized Seyfert nuclei. For nearly all such candidates, we based this interpretation on new, high quality optical spectra which reveal subtle Seyfert features that were missed in previous studies. The same conclusion about the lack of high-$L_X$ starbursts can be drawn from the results of the *Einstein/IRAS* study of David, Jones, & Forman (1992).

However, E 0336−248 is an exception in that it does *not* harbor an AGN optically, and therefore requires a better X-ray position to unambiguously test the association of the galaxy with the X-ray source. Without this positional information, there will always remain the additional possibility that weak, broad emission lines which were previously present might have faded, or might be highly reddened as they sometimes are in intermediate-type Seyfert galaxies (e.g., Goodrich 1995), and that the AGN is simply dormant.

There are several clues that led us to suspect that the X-ray source E 0336−248 was misidentified optically. First, the original X-ray position is of exceptionally poor quality, as the source was partly occulted by the rib of the *Einstein* IPC. Perversely, a serendipitous detection of E 0336−248 by the *ROSAT* PSPC fails to resolve the identification question because the source is 40′ off-axis where the point spread function is very large and the position uncertain. Nevertheless, we have analyzed the PSPC spectrum of this source, finding that it indeed is fitted by a typical AGN power-law. Finally, we inspected the ESO Sky Survey plates for plausible alternative identifications, and found that there is a blue object near the plate limit, about 52″ north of the galaxy, which is not visible on the POSS

plates. There are several less unusual stars within the error circle as well. The faint blue object, whose position is consistent with both the IPC and PSPC position, is a plausible AGN identification. At magnitude $\sim 20$, its X-ray/optical flux ratio would be somewhat on the high side for QSOs, but not exceptionally so. Alternatively, it might be a BL Lac object.

Now that we have obtained a *ROSAT* HRI observation of this field, our suspicions were confirmed. There is a single, point-like X-ray source that is *not* coincident with the galaxy, but with a faint object about $77''$ north of it, even further than we had initally suspected. Our primary objective has therefore been attained, and will be reported in a paper to be written about this and other X-ray sources for which similar problems are under investigation by our X-ray and optical team. However, since the actual optical counterpart of E 0336–248 is *not* the blue object that we had suspected initially, we are interested in doing optical spectroscopy to investigate the nature of the optical counterpart and its blue neighbor. Both objects might be members of the same group or cluster, for example. We hope to use some observing time that we already have lined up this fall for this purpose.

## 6. EGRET Sources at Intermediate Galactic Latitude

The identity of the persistent high-energy ($> 100$ MeV) $\gamma$-ray sources in the Galaxy is still largely a mystery. The second installment of the EGRET (2EG) (Thompson et al. 1995) lists a total of 128 sources, of which 51 are likely or possibly identified with AGNs (Montigny et al. 1995), five with rotation-powered pulsars (Thompson et al. 1994), and one is the LMC (Sreekumar et al. 1992). There are 71 unidentified sources, of which 33, or almost half, lie in the narrow band of $|b| \leq 10°$ along the Galactic plane. This excess of low-latitude sources must, therefore, constitute a Galactic population that is either similar to the already identified $\gamma$-ray pulsars, or an entirely new class of $\gamma$-ray emitters associated with the disk population. We are contining our program, begun in AO6, that is aimed at intermediate-latitude sources, arguing that X-ray detection of them is the most plausible method of identifying the Galactic population. The sources at high latitude must statistically be mostly AGNs, and are more straightforwardly identified through radio and optical means.

The Galactic sources will be difficult to identify. We first describe the observational and theoretical constraints that affect the ability of ROSAT to make an identification of any particular EGRET source. We then describe the choice of targets for which ROSAT is optimally suited, and argue that if they have X-ray properties like any of the already identified sources, then we expect to identify them through followup optical and radio observations of HRI sources detected in their $\gamma$-ray error circles. Indeed, X-ray detection may be the *only* means of identifying the majority of EGRET Galactic sources if, as many think, they are pulsars that are radio quiet, or whose narrow radio beams do not cross the earth.

Rotation-powered pulsars seem most likely to explain the Galactic $\gamma$-ray source population. The shapes of radio pulsar beams as determined by the highly successful rotating vector model (Radhakrishnan & Cooke 1969) demand that the majority, $\sim 70\%$ of young radio pulsars, are *not* visible from Earth. The clear differences between the broad $\gamma$-ray

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beam patterns and the narrow radio pulses implies that $\gamma$-ray emission is probably visible from a much wider range of directions than are the radio beams. Indeed, the ROSAT identification of the high-energy $\gamma$-ray source Geminga as the first radio quiet, but otherwise ordinary pulsar (Halpern & Holt 1992), provides what might be the prototype for the remaining unidentified Galactic sources. Nearly all predictions of the $\gamma$-ray pulsar population begin with the understanding that radio detection of most $\gamma$-ray pulsars is not a necessary or even an expected occurrence, although a few more radio pulsars may be responsible for EGRET sources that have too few $\gamma$-ray photons to reveal their corresponding periods.

Several authors have considered the pulsar hypothesis from statistical or theoretical points of view. Beginning with the properties of the identified EGRET pulsars (Table 1), Halpern & Ruderman (1993) parameterized the observed increase of $\gamma$-ray efficiency $\eta$ with age as $\eta = 0.2\,\tau_5$, where $\tau_5$ is the age in units of $10^5$ yr. Using the estimated birth rate of pulsars in the solar neighborhood, they estimated that approximately 23 $\gamma$-ray pulsars should be visible to a threshold of $3 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$, and that the typical distance would be $\sim 1.5$ kpc for an assumed scale height of $3°$. This total number of 23 would be reduced by any beaming factor that prevents detection through a full $4\pi$ steradians. One of the interesting consequences of this scenario is that most pulsars manage to maintain a roughly constant $\gamma$-ray luminosity of $\sim 3 \times 10^{34}$ ergs s$^{-1}$ while spinning down, until the efficiency of this process approaches unity. Indeed, Table 1, in which the pulsars are ordered according to decreasing spin-down power $I\Omega\dot{\Omega}$, clearly shows the corresponding increase in $\gamma$-ray efficiency.

The most detailed theoretical treatment of the pulsar model for the Galactic $\gamma$-ray sources is that of Romani & Yadigaroglu (1995) and Yadigaroglu & Romani (1995). They developed a numerical calculation of $\gamma$-ray production and beaming in the outer-gap model that successfully reproduces the basic observed features of the pulse profiles and the $\gamma$-ray efficiency as a function of age. By combining this model with a Monte Carlo simulation of the Galactic pulsar population, they estimated that a total of 22 pulsars should be

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detected by EGRET at the same flux threshold as was adopted by Halpern & Ruderman (1993), which also approximates the threshold of the first EGRET catalog. This number is remarkably close to the earlier back-of-the-envelope calculation, and to the actual number of EGRET sources. A further result of this simulation is that the mean distance to unidentified $\gamma$-ray pulsars should decrease from 3.5 to less than 1 kpc as the age increases from $10^4$ to $10^6$ yr. Most pulsars are old, of course, and therefore nearby.

If we adopt these pulsar scenarios as the most likely description of the Galactic $\gamma$-ray source population, then we should look at the soft X-ray properties of Geminga and the other older pulsars as a guide to planning ROSAT identifications. All of these were detected by ROSAT, with some combination of nonthermal emission, and thermal emission from the surface of the neutron star. The latter is the hallmark of all the older pulsars, with surface temperatures ranging from $5 \times 10^5$ K in Geminga (Halpern & Ruderman 1993) and $7 \times 10^5$ K in PSR 1055–52 (Ögelman & Finley 1993), to $1.5 \times 10^6$ K in Vela (Ögelman, Finley, & Zimmermann 1993). Since most of the $\gamma$-ray pulsars are likely to fall in this older age range, we should base our target selection and exposure times on the feasibility of detecting thermal emission, which is the only significant source of X-rays in older pulsars. In fact, there is some evidence that in $\gamma$-ray pulsars, the accelerator is responsible for reheating the surface of the neutron star when particles strike the surface (Halpern & Ruderman 1993). PSR 1055–52 is hotter than expected for its age from the standard cooling curves. The X-rays and $\gamma$-rays may together sustain the accelerator through pair production. Thus the close association between soft X-ray detected pulsars and high-energy $\gamma$-ray sources.

Our basic strategy is to map the error circles of the EGRET sources, looking for sources that may be identified with neutron stars either through their pointlike, thermal emission, or possibly a compact synchrotron nebula in the case of a younger pulsar. Since the HRI does not have the throughput in most cases to detect enough photons to discover a period, the identification of the X-ray source with a neutron star will depend primarily

on followup optical observations to establish the nature (or absence!) of a faint optical counterpart, or possibly a search for a faint radio pulsar counterpart.

For a number of reasons, we can optimize our chances of success by choosing three targets that are found at "intermediate" Galactic latitudes, $3° < |b| < 20°$, and that are not apparently variable. The advantage of this choice is that it increases the likelihood that (a) the source is real, (b) its position is not affected by errors in the diffuse emission model or nearby weak sources, (c) it is nearby, (d) the column density is not too high, and (e) the corresponding optical fields are not too crowded. The absence of variability is important, since the known $\gamma$-ray pulsars show little if any change, while the AGNs are often dramatically variable.

The height above the Galactic plane at which a pulsar will be found is determined by its birth in a young stellar population with scale height $\sim 80$ pc, and the high velocity which will carry it away from the plane with a mean $z$-component of 260 km s$^{-1}$ (newly determined by Lyne & Lorimer 1994). Thus, after a time of $10^5$ yr, the average pulsar will be found at a height of $\sim 100$ pc, and after $10^6$ yr, at $\sim 350$ pc. Since both observation and theory say that $\gamma$-ray pulsars will be detectable in this age range and at a typical distance of 1–1.5 kpc, the corresponding angular distance from the plane for these typical values is $4° - 20°$, which accounts for our Galactic latitude selection. Older pulsars will have even a larger height and a smaller distance, and Mukherjee et al. (1995) showed that there is statistical evidence for some of them at higher latitudes.

In AO6, we were given 3 targets at Galactic latitudes $3° < |b| < 8°$, and encouraged to continue this program in future AOs. Each of these fields was to be covered with four overlapping HRI pointings. The HRI has a 38′ square field. Four pointings whose centers are separated by 27′, cover a 54′ diameter that includes the entire 95% error ellipse in each case. Two of these fields were observed in March 1996, and we are now beginning the process of trying to identify X-ray sources detected therein. The third field is in thr *ROSAT* timeline for August 1996. For each of these three fields, we also obtained

VLA observations on March 31, 1996 to help in the identification of the X-ray sources, and to look for plausible pulsar candidates. We designed the VLA observing program to be sensitive to pulsars by concentrating on low-frequency, 327 MHz mapping. Pulsars are steep-spectrum sources, and could be identified by comparison of our 327 MHz and 1490 MHz maps. The analysis of 327 MHz data is difficult, and has only just begun.

We were just assigned two additional targets in AO7. We will soon request VLA observations of the one northern field, 2EG J1635–1427, as we did for our three fields from AO6. The VLA observations are designed to permit the detection of pulsar candidates by looking for steep-spectrum sources, those that are bright at 327 MHz relative to 1490 MHz.

This proposal focuses on the properties of pulsars, because that scenario is the one most dependent upon X-ray searches for identification, and the one with the most stringent requirements on the feasibility. But what if the counterpart is not a pulsar? Although none of these sources has a plausible blazar counterpart (Mattox et al. 1996), it cannot be excluded that an errant blazar will be lurking behind the Galactic plane. ROSAT is ideally suited to discovering a new type of $\gamma$-ray AGN, the long-hypothesized "radio-quiet blazar". Other types of Galactic counterparts are much rarer, but easier to identify. The Gregory-Taylor binary LSI +61°303 as a possible counterpart of 2CG 135+01 is a serious example, as is Cygnus X-3 for 2EG J2033+4112. These are bright X-ray sources, well detected by *Einstein* and ROSAT. Optical and radio followups of ROSAT sources will likely be necessary to support the identification process, but ROSAT must begin it.

# APPENDIX

Papers Published Under NASA Grant NAG 5-1935

During the Period 1 November 1994 – 31 October 1995

"No X-ray–Luminous Starbursts in the *Einstein* Medium Sensitivity Survey, Either," Halpern, J. P., Helfand, D. J., & Moran, E. C., *Ap. J.*, **453**, 611 (1995).

"A Possible X-ray Detection of the Binary Millisecond Pulsar J1012+5307," J. P. Halpern, *Ap. J. (Letters)*, **459**, L9 (1996).

"Soft X-ray Properties of the Binary Millisecond Pulsar J0437-4715," **462**, 908 (1996).

"X-ray Spectra of Cataclysmic Variables from ROSAT," Richman, H. R., *Ap. J.*, **462**, 404 (1996).

"A Long *EUVE* Observation of the Seyfert Galaxy RX J0437.4–4711," Halpern, J. P., & Marshall, H. L., *Ap. J.*, **464**, 760 (1996).

"*ROSAT* PSPC and HRI Observations of the Composite Starburst/Seyefert 2 Galaxy NGC 1672," Brandt, W. N., Halpern, J. P., & Iwasawa, K., *M.N.R.A.S.*, **281**, 687 (1996).

Papers Submitted Under NASA Grant NAG 5-1935

During the Period 1 November 1995 – 31 October 1996

"The Geminga Pulsar: Soft X-ray Variability and an *EUVE* Observation," J. P. Halpern, C. Martin, & H. L. Marshall, *Ap. J. (Letters)*, submitted (1996).

"A Broad-Band X-ray Study of the Geminga Pulsar," J. P. Halpern & F. Y.-H. Wang, *Ap. J.*, submitted (1996).

"Extreme X-ray Variability in the Narrow-Line QSO PHL 1092," K. Forster & J. P. Halpern, *Ap. J.*, in press (1996).

"Classification of *IRAS*-Selected X-ray Galaxies in the *ROSAT* All-Sky Survey," E. C. Moran, J. P. Halpern, & D. J. Helfand, *Ap. J. Suppl.*, in press (1996).